

REGULARITY OF THE LARGE-SCALE STRUCTURE OF THE UNIVERSE

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1. Introduction

The observed structure of the Universe is hierarchical. Galaxies and clusters of galaxies are concentrated within elongated filamentary chains of various richness. High-density regions of the Universe form superclusters consisting of one or several clusters of galaxies and chains of galaxies surrounding and joining clusters. The space between filaments is void of galaxies. Superclusters and voids form a continuous network of alternating high- and low-density regions in the Universe.

Systems of galaxies are formed by density waves of wavelength which correspond to the size of system. It is believed that density waves have a Gaussian distribution; on small scales the distribution of galaxy systems is actually well represented by a random process. There exists, however, growing evidence that on larger scales the distribution may have some regularity. In particular, the supercluster-void network shows the presence of a non-random character in the distribution. In this talk I shall discuss this evidence and its possible explanation.

2. Evidence for the regular location of high-density regions

Already first studies of the distribution of superclusters and voids have shown that large cluster-defined voids are surrounded by superclusters and resemble cells with low-density interiors and high-density environs. Examples are the Northern Local Void surrounded by the Local, Coma and Hercules superclusters, and the Bootes void located between the Hercules, Bootes and several other superclusters (Jõeveer and Einasto, 1978; Kirshner *et al.*, 1981; Lindner *et al.*, 1995). Cluster defined voids have a rather large size, of the order of $100 h_{100}^{-1}$ Mpc (Zeldovich *et al.*, 1982).

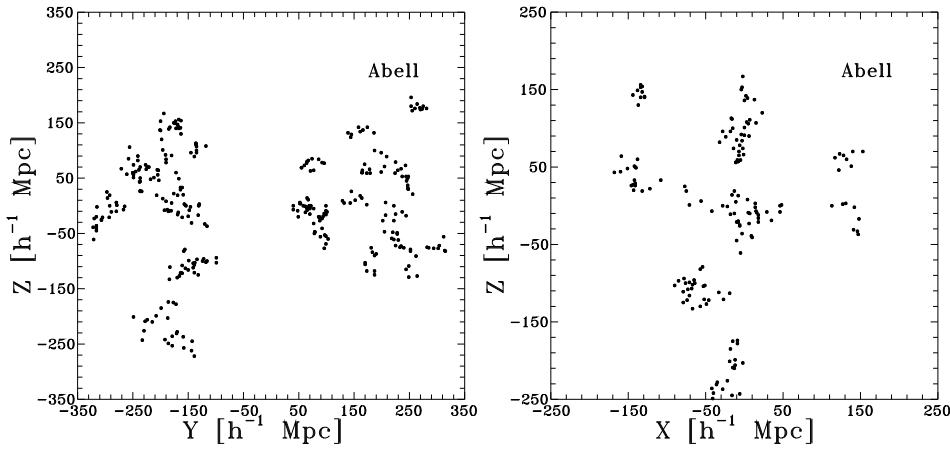


Figure 1. Distribution of Abell-ACO clusters in high-density regions in supergalactic coordinates. Only clusters in superclusters with at least 8 members are plotted. The supergalactic $Y = 0$ plane coincides almost exactly with the Galactic equatorial plane and marks the Galactic zone of avoidance. In the left panel some superclusters overlap due to projection, in the right panel only clusters in the southern Galactic hemisphere are plotted and the projection effect is small.

A similar scale was found from the study of the cluster correlation function which has a secondary maximum near $130 h_{100}^{-1}$ Mpc due to the concentration of clusters in superclusters on the other side of large voids (Kopylov *et al.*, 1988; Mo *et al.*, 1992; Einasto and Gramann, 1993; Fetisova *et al.*, 1993). However, these early studies did not ask the question: Has the supercluster-void network some large-scale regularity?

The first clear evidence for the existence of a regularity in the distribution of galaxies on large scales came from the pencil beams around the northern and southern Galactic pole (Broadhurst *et al.*, 1990). It was demonstrated that high- and low-density regions in the distribution of galaxies alternate with a rather constant step of $128 h_{100}^{-1}$ Mpc. Nearest peaks in the distribution of galaxies coincide in position and redshift with superclusters (Bahcall, 1991), thus one may conclude that the regularity should be a property of high-density regions in the Universe in general. This discovery raised many questions. The basic counter-argument was that on the basis of an one-dimensional survey one cannot draw conclusions on the distribution of matter in three dimensions.

To investigate the global regularity of the supercluster-void network our group in Tartu used Abell-ACO clusters of galaxies (Abell, 1958; Abell *et al.*, 1989). This is the deepest all-sky survey available presently. To understand the nature of the distribution we used first cosmographic approach, and plotted clusters of galaxies in superclusters of various richness to show their

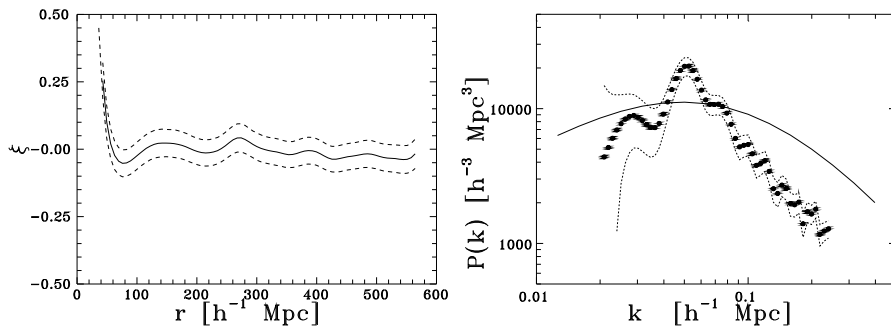


Figure 2. The correlation function (left panel) and the power spectrum (right panel) for clusters of galaxies. Dashed lines show the error corridor. The solid line in the right panel shows the power spectrum of the standard CDM model ($h = 0.5$, $\Omega = 1$). The amplitude of the cluster power spectrum was decreased by a bias factor $b^2 = 3^2$.

dependence on the large-scale environment. Plots of Abell-ACO clusters of galaxies located in very rich superclusters with at least 8 member-clusters are shown in Figure 1 (Einasto *et al.*, 1994; Einasto, 1995; Einasto *et al.*, 1997b). We see a quasi-regular network of superclusters and voids. High-density regions are separated from each other by roughly constant intervals of $\approx 120 h_{100}^{-1}$ Mpc.

3. The correlation function and the power spectrum of clusters of galaxies

The correlation function of a quasi-regular network of clusters of galaxies should have periodic maxima and minima which correspond to mutual distances of high- and low-density regions. This phenomenon is actually observed; see Figure 2 (Einasto *et al.* 1997a). The power spectrum of clusters of galaxies is also shown in Figure 2 (Einasto *et al.*, 1997a), it was determined from the correlation function using the Fourier transform. The power spectrum is peaked on wavelength $\lambda_0 = 120 h_{100}^{-1}$ Mpc which corresponds to the size of the step of the supercluster-void network. On short wavelengths the spectrum can be approximated by a power law with index $n = -1.8$. On long wavelengths the spectrum is not well determined, within observational errors it is compatible with the Harrison-Zeldovich spectrum which has power index $n = 1$.

Recent investigations of the power spectrum of galaxies and clusters of galaxies demonstrate similar behaviour of the spectrum on large scales. Peacock (1997) and Gaztanaga and Baugh (1997) determined the three-dimensional power spectrum from the projected distribution of APM galaxies; Retzlaff *et al.* (1997) used Abell-ACO clusters of galaxies but a completely independent method of data analysis; Tadros *et al.* (1997) calculated

the power spectrum for APM clusters. These four independent studies show that the power spectrum on scales shorter than $\approx 120 h_{100}^{-1}$ Mpc is approximately a power law with index between $n = -1.8$ and $n = -1.9$; the spectrum has a rather sharp maximum near the wavelength $120 h_{100}^{-1}$ Mpc, and approaches the Harrison-Zeldovich regime on longer wavelengths. The exact position of the maximum and the shape of the spectrum near the maximum vary between studies, but these variations are well in the limits expected from errors of the determination of the power spectrum.

4. Comparison with CMB data

The present matter power spectrum is generated by two different processes: by the inflation of the Universe, and by the hot radiation dominated era before recombination. Inflation determines the initial power spectrum of matter. During the hot phase density fluctuations within the horizon are damped, thus on small wavelengths the amplitude of the spectrum decreases; this behaviour is described by the transfer function. The transfer function is given by cosmological parameters: the density of matter in various populations (baryon, cold and hot dark matter), the Hubble constant etc. To estimate the possible role of these processes Atrio-Barandela *et al.* (1997) performed calculations of the angular spectrum of temperature anisotropy of the cosmic microwave background (CMB). The temperature anisotropy spectrum has a maximum around wavenumber $l \approx 200$ due to acoustic oscillations of the hot plasma before recombination. The shape of the angular spectrum around this maximum is very sensitive to the initial spectrum and cosmological parameters, and can be used as a test.

Calculations were performed for the standard CDM-type model with a scale-free initial spectrum (which has a constant power index $n \approx 1$), and two models with the peaked power spectrum. For a set of cosmological parameters, Atrio-Barandela *et al.* find the matter transfer function, and the matter and radiation power spectra. It is assumed that the Universe has a flat geometry. For the calculations the CMBFAST package was used (Seljak and Zaldarriaga, 1996). To estimate the goodness of a fit of a particular set of cosmological parameters authors calculate parameter χ^2 comparing model data with observations made in Saskatoon (Netterfield *et al.*, 1997).

Recent measurements favour a low density of matter in the Universe, but an open Universe seems to be excluded as in this case the first acoustic maximum of CMB angular spectrum shifts to too high frequencies. Thus a CDM model with large cosmological constant is of particular interest. In a model with large cosmological constant the baryon density is comparable to the density of the dark matter, and acoustic oscillations of the hot plasma before recombination have an enhanced amplitude (Szalay, 1997).

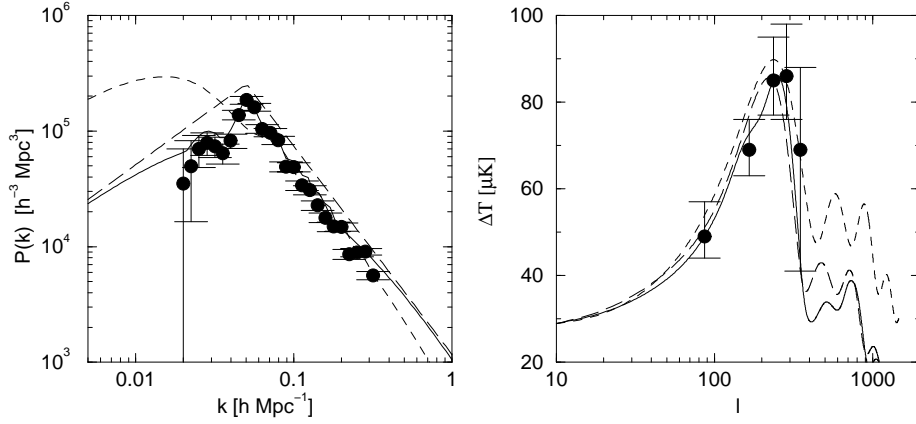


Figure 3. Comparison of matter power spectra and radiation temperature anisotropy spectra with cluster and CMB data. Dots with 1σ error bars give the observations: the measured cluster spectrum (Einasto *et al.* 1997a) in the left panel and the Saskatoon data on CMB temperature anisotropies (Netterfield *et al.* 1997) in the right panel. The scale-free model spectra (short-dashed lines) were computed using the following parameters: $h = 0.6$, $\Omega_b = 0.07$, $\Omega_c = 0.23$, and $\Omega_\Lambda = 0.7$. The cluster spectrum based model (solid lines) was calculated using $h = 0.6$, $\Omega_b = 0.08$, $\Omega_c = 0.92$, and $\Omega_\Lambda = 0$; the double power approximation of the peaked spectrum (long-dashed lines) using $h = 0.6$, $\Omega_b = 0.05$, $\Omega_c = 0.95$, and $\Omega_\Lambda = 0$. To compare matter power spectra and observed cluster spectrum we used a bias factor $b_{cl} \approx 3$ for clusters.

This model can be considered as a candidate for the peaked power spectrum.

Calculations by Atrio-Barandela *et al.* show that, using an appropriate set of cosmological parameters, temperature anisotropy spectra of different models are very similar in the range of multipoles observed in the Saskatoon data (see Figure 3). In other words, the present CMB data are not sufficient to discriminate between models. The matter power spectra are also similar on short wavelengths, but on medium and long scales they are different. The scale-free model with a large cosmological constant has a broad maximum at large wavenumber ($k \approx 0.01 h_{100} \text{ Mpc}^{-1}$); the maximum of the first acoustic oscillation occurs at $k \approx 0.1 h_{100} \text{ Mpc}^{-1}$, and is of rather small relative amplitude. Both scales are outside the allowed range of the position of the spike in the cluster spectrum: $k_0 = 0.052 \pm 0.005 h_{100} \text{ Mpc}^{-1}$ (Einasto *et al.*, 1997a). Thus the observed spike is not related to acoustic oscillations in the baryon-photon plasma as assumed by Szalay (1997) but must have a different origin.

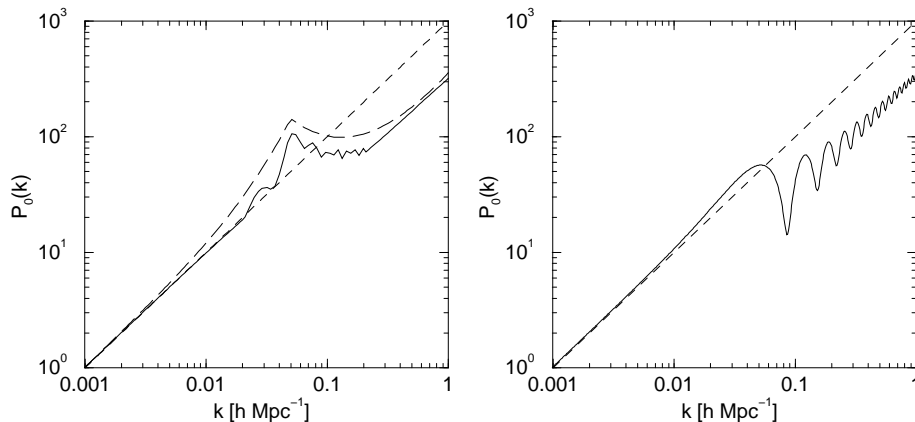


Figure 4. Initial power spectra. The left panel shows initial power spectra for models, calculated for parameters listed in the caption of Figure 3. The right panel gives a theoretical initial power spectrum suggested by Starobinsky; the dashed line shows for comparison the standard scale-free initial power spectrum.

5. Initial spectrum

The initial power spectra for our models are shown in Figure 4. We see that the presence of a peak in the present power spectrum leads to a peak also in the initial spectrum. Another important deviation of the initial spectrum calculated from the observed spectrum is the presence of a break: the amplitude of the spectrum on shorter wavelengths is smaller than that expected for a single scale-free spectrum. The initial spectrum found from the observed power spectrum has three parameters: the position and relative height of the peak, and the relative amplitude of the break in respect to the scale-free spectrum.

It is interesting to note that an initial power spectrum similar to those found from the observed cluster spectrum was suggested by Starobinsky (1992). Starobinsky assumed that the inflation of the Universe may have had a more complicated form than usually accepted. If the inflaton field was evolving through a non-smooth point of its potential then a change in the first derivative of the potential generates a spike followed by a break in the initial spectrum. Such an initial spectrum is shown in the right panel of Figure 4.

6. Evolution of the structure

To investigate the influence of various regions of the power spectrum to the structure of the Universe we performed N-body calculations of several sim-

ple models with a constant power index $n \approx -1.5$ on small scales (wavenumber $k \geq k_0$), a maximum at the wavenumber $k = k_0$, and various shape and power indices at longer wavelengths (Einasto and Gramann, 1993; Frisch *et al.*, 1995).

This test shows that the fine structure of superclusters is entirely given by density waves shorter than the maximum of the spectrum. The scale of the supercluster-void network is fixed by the wavelength of the maximum of the spectrum, $\lambda_0 = 2\pi/k_0$. Long waves modulate the structure: if there is no power on longer scales then all supercluster have practically equal masses and are regularly distributed. The variance of supercluster masses and relative distances increases if one raises the amplitude of the spectrum at long wavelengths. The shape of the spectrum around the maximum determines the regularity of the supercluster-void network. If the transition from a positive spectral index at long wavelengths (Harrison-Zeldovich spectrum) to a negative index at small scales is sudden then the network is fairly regular. On the other hand, if the transition is smooth then the network is irregular.

Density perturbations of medium and small scale located at the top of density waves having the largest amplitude give rise to the formation of superclusters of galaxies. Here the overall amplitude of perturbations is the largest, respective small-scale systems (clusters and groups of galaxies) have large masses, they form first and evolve more rapidly. On the contrary, similar medium and small-scale perturbations located near the minima of large-scale density waves have a low overall amplitude, respective systems of galaxies have small masses, and their formation starts later. Thus our simple models explain the hierarchy of galaxy systems and show why large cluster-defined voids are not empty but contain galaxy systems similar to superclusters but with much lower masses (Zeldovich *et al.*, 1982; Lindner *et al.*, 1995). These simple models also show the importance of the study of the distribution of superclusters – they are determined by the behaviour of the power spectrum near its maximum. In this region differences between various cosmological models are the largest.

7. Discussion

The comparison of optical and CMB spectra has shown that no combination of cosmological parameters can reproduce the spike at $k = k_0$: the existence of a broad maximum is an intrinsic property of all scale-free models. A universe with a smooth maximum of the matter power spectrum and randomly distributed phases of density fluctuations will have a random distribution of high- and low-density regions (Einasto *et al.*, 1997c; Einasto *et al.*, 1997d). Such a distribution is in contradiction with the distribution of superclusters. Thus present data favour the interpretation of

the observed spectrum in terms of a peaked, broken scale initial spectrum.

Present data are, however, not accurate enough to make a final decision on the initial power spectrum of matter. One point of concern is the power spectrum itself: Is the power spectrum at all an appropriate statistic to give a full description of the distribution of matter in the Universe? As Szalay (1997) has shown, a change of phases for two distributions having identical power spectra may change the appearance dramatically. A simple toy model with a regular cellular structure after phase scrambling transforms to a completely random sample. As the Universe on scales of the supercluster-void network definitely has some regularity, then phase information seems to be essential to describe the structure. So far no appropriate statistic has been suggested.

Another point of concern has been the use of Abell-ACO clusters as indicators of the large-scale structure. Several authors have argued that this catalogue may contain systematic errors, and the use of a machine-selected catalogue of clusters as the APM catalogue is to be preferred. To check this point we have compared the distribution of Abell-ACO and APM clusters of galaxies in rich superclusters. This analysis shows that rich superclusters found on the basis of these completely independent cluster samples are very similar. Quantitative tests lead to similar conclusions (Einasto *et al.*, 1994). On the other hand, the volume covered by the APM sample is much smaller than the volume covered by the Abell-ACO sample. Following Jõeveer and Einasto (1978) and Zeldovich *et al.* (1982) we call large low-density regions surrounded by superclusters as cells. The APM sample covers just 1 – 2 such cells only in the southern Galactic hemisphere whereas the Abell-ACO sample contains information on a dozen of cells in both hemispheres. Thus, to study the large-scale distribution of high-density regions, the Abell-ACO sample is much better suited.

The comparison of CMB and matter spectra shows that definite differences between models with scale-free and peaked initial power spectra are expected for small angular scales in the CMB spectrum, and on very large scales in the present matter spectrum. Future experiments, both for optical and CMB regions, are concentrated on these wavelengths. Thus the choice between the models will be much easier in the near future.

Whatever the answers to these questions are, one can say that the distribution of high-density regions in the Universe brings us information on the very early stages of its evolution.

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